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Groundwater Plume Control With Phytotechnologies at Argonne National Laboratory

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GROUNDWATER PLUME CONTROL WITH PHYTOTECHNOLOGIES AT ARGONNE NATIONAL LABORATORY-EAST

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ABSTRACT

In 1999, Argonne National Laboratory-East (ANL-E) designed and installed a series of engineered plantings consisting of a vegetative cover system and approximately 800 hybrid poplars and willows rooting at various predetermined depths. The plants were installed using various methods including Applied Natural Science's TreeWell® system. The goal of the installation was to protect downgradient surface and groundwater by hydraulic control of the contaminated plume. This goal was to be accomplished by intercepting the contaminated groundwater with the tree roots, removing moisture from the upgradient soil area, reducing water infiltration, preventing soil erosion, degrading and/or transpiring the residual VOCs, and removing tritium from the subsoil and groundwater.

The U.S. EPA Superfund Innovative Technology Evaluation Program (SITE) and ANL-E evaluated the demonstration. The effectiveness of the various plantings was monitored directly through groundwater measurements and samples, and indirectly via soil moisture probes, plant tissue analysis, microbial studies, geochemical analysis, and sap flow monitoring. A weather station with data logging equipment was installed. ANL-E modeled the predicted effect of the plants on the groundwater using MODFLOW. The demonstration has lasted three growing seasons and continues.

This paper presents the results of the sampling, monitoring, and modeling efforts to date. The project was not only successful in reducing the groundwater contaminant flow and the contaminants at the source; it also provides insight into the techniques that are useful for measuring and predicting the effectiveness of future similar projects.

INTRODUCTION

The 317/319 Area at Argonne National Laboratory-East (ANL-E) (approximately 2 hectares of surface) contains several release sites used in the past to dispose of solid and liquid waste from various laboratory activities. Because of these past activities, VOCs and tritium have been released in the groundwater at depths of approximately 6-9 m and have been detected in groundwater offsite. The U.S. Department of Energy (DOE) Accelerated Site Technology Deployment (ASTD) program, along with the EM-50, Subsurface Contaminant Focus Area, have funded ANL-E to deploy a phytoremediation system instead of the traditional technology of pump-and-treat on the basis of phytoremediation being more cost effective and better suited than mechanical extraction wells (currently removing groundwater as an interim measure) and an asphalt cap to achieve project goals.

Soon after DOE funded the project, the U.S. EPA and DOE agreed to include this deployment in the projects evaluated by the U.S. EPA Superfund Innovative Technology Evaluation (SITE) Program. Under this program, the U.S. EPA through its National Risk Management and Research Laboratory (NRMRL) independently monitored and evaluated the technology's performance at the ANL-E 317/319 site in addition to the scheduled monitoring activities conducted by ANL-E. Groundwater, soil, plant tissue, and transpirate have been collected and analyzed by the different organizations participating to the project at regular intervals to determine the performance of the installation.

As part of the deployment efforts, approximately 800 hybrid poplars and willows were planted in the summer of 1999 in and downgradient of the 317/319 Area at varying, predetermined depths as an engineered plantation. These trees have been planted so that root development targets the areas of soil and groundwater contamination, using methods that include the TreeWell® system patented by Applied Natural Sciences, Inc. In addition, a vegetative cover of herbaceous plants has been seeded among the trees to control soil erosion and minimize water infiltration. Appropriate control cells have been set up at the ANL-E greenhouse area (a clean area on site) to represent background conditions. Figure 1 depicts the remediation area: in the upgradient VOC source area (FD) hybrid willow trees were planted so that their roots could freely explore the contaminated soil and take up water and entrained chemicals. In the downgradient area of groundwater contamination (hydraulic control area, or HC), hybrid poplars were planted using the TreeWell® technology so that their roots were isolated from surficial aquifers and forced to extend downwards to the deeper, contaminated groundwater.

The monitoring efforts had the purpose of determining and documenting the system's effectiveness in achieving the remediation objectives. Activities involved:

- Monitoring the health and growth of the planted trees and the herbaceous cover
- Modeling and confirming water use and hydraulic control
- Determining changes in groundwater concentration of contaminants
- Determining the uptake and degradation of the volatile contaminants in the plant tissue to document source reduction.

MONITORING PROTOCOLS

Tree Growth and Health

Tree vital measurements were monitored by periodically measuring the height of the above ground stem (or tallest branch) and the diameter of the stem at 30 cm above ground level. Approximately 10% of the trees were randomly selected for these measurements. Visual inspections were also carried out throughout the year to monitor aspect, presence of leaves, and branching, mortality, and presence of insects or other pests on the trees.

Three observation areas for the herbaceous cover were also randomly chosen and established. Observations were conducted periodically and included the determination of % plant cover versus bare soil, and % coverage for each herbaceous species. From a reference tree center, using a sighting compass, a measuring tape was directed outwards at 160° from the tree. A 1 m^2 rigid quadrant (the survey area) was then placed on the ground, parallel to the tape on its west side at 1 m from the tree. The percent cover was defined as the amount of ground surface covered by living parts of plants, including but not limited to leaves.

Sap Flow, Hydraulic Control Modeling, and Verification
In order to understand the effects of the plantings on the target groundwater and contaminants, several monitoring approaches were applied: estimation of consumption by trees through sap flow measurements compared to available precipitation and calculated evapo-transpiration, nearly continuous direct measurement of groundwater levels, and groundwater modeling based on the measurements and estimates.

To assess water consumption via tree transpiration, hence the effectiveness of the hydraulic containment system, sap velocity measurements were conducted on seven hybrid poplar trees in the 317/319 HC Area. These measurements were carried out continuously during August 2000 and again during June through September 2001 using thermal dissipation probes (TDPs). The TDP probe (Dynamax, Houston, TX) has two thermocouple needles inserted in the sapwood, the upper one containing a heating element under constant voltage. The probe needles measure the temperature difference between the heated needle and the sapwood ambient temperature below. The temperature difference under flow conditions and the maximum temperature difference at zero flow provide a direct conversion to sap velocity.

Data were collected from trees randomly located within approximately 30 m of the position of a data collection system installed in the field. Cross-sectional areas of the stems (at the levels of the TDPs) were collected for these trees. The data collected from TDPs were related empirically to sap velocity (Granier, 1985) and the product of sap velocity and cross-sectional area yielded the rate of sap flow (L day^{-1}).

Sapflow measurements on individual trees were used to estimate stand-level transpiration rates. The sapflow data were used to (1) compare transpiration rates changes from year to year, assess monthly variations in sapflow rates during the 2001 growing season, and (2) determine stand-level water usage at the height of the 2001 growing season.

As a means of evaluating the potential of the phytoremedial plantation for hydraulic containment, a finite-difference numerical flow model was constructed by Quinn et al. (2001). This model used the U.S. Geological Survey code MODFLOW (MacDonald and Harbaugh, 1988) and was focused on the confined, perched, glacial drift aquifer that extends below much of the 317/319 Area at a depth of approximately 7.6 m (25 ft) below grade. Modeling was initially directed toward calibrating to seasonally changing hydraulic heads based on over ten years of water level measurements at site wells. Then the effect of the TreeWells® of the plantation was incorporated by assuming a best estimate for the water use of the trees under luxury consumption conditions. Both the growth phase and the mature phase of the plantations were modeled.

In November 1999, as part of the phytoremediation system-monitoring program, seven water level sensors (Druck model PDCR 1830, with vented cable) were installed in monitoring wells in the 317 and 319 Areas. The water level data, along with weather station data, are collected hourly at several battery or solar-powered data loggers and were used to verify the validity of the predictions generated by the groundwater model.

Groundwater Contaminant Remediation
To assess the effectiveness of groundwater mitigation, samples were collected from thirty-seven groundwater monitoring wells upgradient, downgradient, and within plantations in the 317/319 Areas. Samples were collected via hand bailers using standard techniques and analyzed for VOCs by gas chromatography/mass spectrometry per SW-846 Method 8260 (EPA, 1986). Selected samples were also analyzed for tritium by liquid scintillation spectrometry using EPA Method 906 *(EPA, 1980)*. These measurements were carried out every three months from the second quarter (April-June) of 1999 to the first quarter (January-March) of 2002.

Analyte data were used to (1) examine the ratio of cis-1,2-dichloroethene (c-DCE) to trichloroethene (TCE) as an indicator of reductive dechlorination in the French Drain, (2) estimate the removal efficiency of VOCs in the 317 Area HC plantation, and (3) note the change in tritium activity in the 319 Area HC plantation.

Contaminant Uptake and Source Reduction
While it is known (Newman et al. 1997, Gatliff et al. 1998) that trees such as poplars and willows are capable of taking up a number of organic compounds (including chlorinated solvents such as TCE, PCE, and carbon tetrachloride), there are varying opinions on the fate of those compounds in the rhizosphere and plant systems. These compounds can be degraded in the root zone (Nzengung et al. 2001), taken into the plant and vented through the bark (Burken 2002), and degraded in leaf tissue (Newman et al., 1999). Portions of these contaminants have also shown to be vented out by the same trees into the air via the transpirative flow or, during winter, by gas diffusion through the plant's air conducting tissue (Nietch et al. 1999, Vroblesky et al. 1999, Davis et al. 1998).

Plant tissue (leaves and stems) was sampled to determine the presence of VOCs and their degradation intermediate trichloroacetic acid (TCAA). Finding VOCs in leaf and/or branch tissue above background levels would provide a clear indication that the trees are indeed taking up the contaminants from soil or groundwater and translocating it to the aboveground tissues. Finding TCAA in these tissues would provide a proof that at least a portion of the parent compounds is being degraded by the plant. In principle, by multiplying contaminant concentrations in the sap-by-sap flow, a measure of contaminant removal by plant uptake can be obtained. In fact, this is still a very imprecise measurement because of unknown diffusion rates from the sap through cell walls into external air, and because it is still unknown how much of the total contaminant detected in tissue is in the freely moving sap and how much is adsorbed to the plant tissues.

Samples of leaves and branches were collected by cutting with a sharp scissors and directly placed into airtight crimped headspace vials. Samples for VOC and TCAA analysis were directly placed into headspace vials for gas chromatographic analysis within 24 hours. While analysis of VOCs was conducted via direct headspace techniques, samples for TCAA analysis were thermally decarboxylated at 90˚C before being analyzed via headspace. Control samples from plants growing in non-contaminated soil were also sampled and analyzed using the same methods. Detection limits were 0.5 ng/g for chloroform, TCAA, TCE, and 0.2 ng/g for PCE.

Samples were collected from more than 30 different trees at the 317 FD area, plus willows at the greenhouse control plots, at various times during the 1999, 2000, and 2001 test periods. In each sampling event, six samples were collected from each sampled tree, including two of branch tissue, and four of leaves growing on that branch.

RESULTS

Tree Growth and Health

During their first year from planting, the trees developed, although at a slower rate than their potential, and successfully established themselves at the site, both at the source area (317 FD) and at the Hydraulic Control Areas (317 and 319 HC). While some of the initial trees had to be replanted, as they did not survive the transplant shock (the trees were planted in an extremely hot and dry weather), the health of those that overcame the transplant (the majority) was more than satisfactory. It is believed that the non-optimal climatic conditions at the time of transplant and throughout the first summer caused the trees to go into a "survival" mode (rather than a fast growth mode), and that a cooler than expected growing season of 2000 slowed down the trees' growth compared to their potential.

The 2001 growing season was overall was more favorable to plant growth than the 2000 season. In the summer of 2001, a number of the poplars started to show the large apical leaves that are a sign of unrestricted water availability. Poplars grew 10 mm in diameter and 109 cm in height. Poplars grew 2.8 more times in height and 1.6 times more in diameter in 2001 compared to 2000. On average, during the 2001 summer, willows increased 7 mm in diameter and 20 cm in height. Compared to the year 2000 growing season, willows grew 2.6 times more in height, while growing at about the same pace in diameter (in 2000 the willows grew substantially more in diameter than in height).

The groundcover species sowed at the site grew according to expectations and were able, by the summer of 2000, to establish themselves as a ground cover and minimize risks of erosion and runoff. In some areas, local vegetation composes a significant portion of the final plant cover, without decreasing the groundcover effectiveness.

Sap Flow, Hydraulic Control Modelin, and Verification

Transpiration is the evaporative loss of water from a plant. Water transport mechanisms move water from the soil zone to the stomata of the leaf where it is lost to the atmosphere. Transpired water can be derived from the near surface soils, and in the case of phreatophytic species, from the capillary fringe or saturated zone. The ability of phreatophytic species to seek and use contaminated groundwater is the basis of this phytoremediation technology. Maximum use of groundwater through the establishment of a deep root zone is critical to the success of a phytoremediation project. The amount of water transpired by the trees throughout the system's life cycle is an important factor in determining the effectiveness of the technology for containment and remediation of a contaminant plume.

Sap flow for the seven-instrumented trees averaged 2.2 L day^{-1} during August 2000 and 3.2 L day^{-1} during August 2001. This represents year-to-year increase of approximately 45%. Sap flow measurements during August 2000 ranged from 0.64 to 6.4 L day^{-1} while the range for

August 2001 was 0.62 to 8.0 L day^{-1}. During the 2001 growing season, the greatest average sapflow rates occurred in July (3.8 L day^{-1}), while the lowest occurred in the month of August (3.2 L day^{-1}).

Stand-level transpiration was calculated as the product of average sap flow results from the instrumented trees (normalized to basal area) and the estimated total basal areas of the hybrid poplars in the 317 HC Area and 319 HC Area. There are 382 poplars in the 317 HC Area and 160 poplars in the 319 HC Area. Maximum stand-level sapflow was calculated to be 1,314 L day^{-1} during July 2001. The year-to-year increase in sap flow as measured in August 2000 and 2001 was approximately 219%, from 360 L day^{-1} to 1149 L day^{-1}.

Groundwater elevation results through December 31, 2001 are shown in Figure 2. The data demonstrates important aspects of the site's hydrogeology and the affect of the young plantation on water levels. In Figure 2, a clear response to precipitation is seen, with hydraulic heads rising within one hour of the onset of precipitation. The magnitude of the water level response is roughly correlated with the amount of rainfall, though smaller wintertime precipitation events may create significant head increases because of concurrent snowmelt.

A closer look at the continuous head data reveals additional details about the effect of the phytoremediation system on the nearby water levels. The 800 trees, including 400 TreeWells® targeting a confined aquifer, were planted in summer 1999. The TreeWells® were planted deep ("up to their shoulders") in order to maximize their initial root depth within their lined boreholes, and they were pruned heavily in order to reduce stress during their hot-weather planting. In 2000, the growing season was cool, with 32˚C (90˚F) not reached until September. During that summer, the trees did not exhibit above ground growth; instead, the cool weather seemed to give them time to establish themselves. A close look at data from the cool 2000-growing season shows no obvious impact of the trees on water levels. However, in September 2000, during the warm period, the plantation began exhibiting diurnal fluctuations (Figure 3). These fluctuations, which are up to 7 cm (0.25 ft) in well 317181, were present to a lesser degree at 317172, 317452, and 317151. Diurnal fluctuations were not present at 317391, which is upgradient of the phytoremediation system, or at the two 319 Area wells 319261 or 319171. The water levels in the 319 Area wells may not be responding due to different hydrologic conditions or a smaller plantation.

The diurnal fluctuations continued during the 2001 growing season and varied in amplitude with the amount of daily solar radiation. What is noteworthy of the 2001 data is that the water levels, such as in well 317181, exhibit a gradual downward trend during days of high sunlight and strong diurnal fluctuations, with gradual recovery of water level during cloudy days that lack strong fluctuations (Figure 4). For this young plantation, this is an early indication of what is expected in the upcoming years, namely that the maturing poplars will exert an increasing effect on the site's hydrology and ultimately result in hydraulic containment. This anticipated containment has been evaluated through groundwater modeling that incorporated the best estimate of water use by the TreeWells® through each month (Quinn et al. 2001). Results suggest that despite leaf-off winter periods, the plantation will provide full containment on the larger western (317 Area) side of the plantation, and a strong degree of containment on the eastern (319 Area) side.

Groundwater Contaminant Remediation

In addition to contributing to remove contaminants by direct uptake, a phytoremediation system may enhance natural biodegradative processes by modifying subsurface conditions from an aerobic state to an anaerobic state that supports reductive dechlorination. Plants may achieve this by providing organic matter (e.g., root matter and exudates) that subsequently, microbially consumes available oxygen, thus driving the system anoxic. Furthermore, phreatophytic species that can reach the saturated zone are better able to promote oxygen depletion due to the low diffusion of oxygen through water. Consequently, microorganisms that promote reductive dechlorination can then degrade the chlorinated contaminants and their breakdown products to innocuous compounds.

Researchers have been investigating the possibility of using trees in the Salicaceae family, which includes poplars and willows, to remediate plumes of VOCs in groundwater. The deep planting method employed in this field demonstration represent an engineered technique designed to reach impacted media in an abbreviated period of time to change subsurface conditions to a regime that support reductive dechlorination. Groundwater sampling data show that such a shift is occurring, with active reductive dechlorination in the French Drain source area and removal of VOCs downgradient in the hydraulic control plantations.

Figure 5 summarizes the ratio of c-DCE to TCE in three French Drain monitoring wells, 317322, 317332, and 317342. This ratio is representative of reductive dechlorination processes due to the biodegradation of TCE to its daughter product, c-DCE. The data reveal that while significant reductive dechlorination has developed over time, it is not consistent throughout the FD. The graph shows that the ratio for 317322 has increased from 1.6 to 14.4, indicating robust microbial activity. By comparison 317332 has remained relatively inactive (0.6-0.8) over the same period. Table 1 compares the most recent analyte data and c-DCE-to-TCE ratio for the three wells. The comparison suggests a relationship between the magnitude of the ratio and the magnitude of the underlying analyte concentrations. Although not the focus of this paper, further study of these trends may produce an estimate of the lower-bound levels of this technology at this site to treat c-DCE and TCE.

The four most prevalent analytes found in groundwater samples from the site were used to estimate VOC removal within the 317 HC Area: 1,1-dichloroethane (DCA), 1,1,1-trichloroethane (TCA), c-DCE and TCE. Table 2 gives the starting and final analyte concentrations and removal efficiencies for two monitoring wells located in the central portion of the 317 HC Area plantation, 317151 and 317181. The data show that the trees are currently achieving moderate removal efficiencies (22% to 49%). Greater reductions are anticipated as the trees mature; however, it is evident that the system is filtering and reducing VOCs migrating into the 317 HC Area plantation.

Figure 6 illustrates the data assembled from 319171 over the course of the demonstration period. Well 319171 is located near the middle of the 319 HC Area plantation. The chart shows a downward trend in the level of tritium in groundwater with an overall decrease of 67% (7,900 to 2,570 pCi/l). Regression analysis of these data (r2=0.85) suggest a tritium half-life of 660 days (a period much shorter than the NIST standard of 4,500 days) thus suggesting that tritium is actually removed from the system rather than being only decreased by natural decay.

Contaminant Uptake and Source Reduction
Figures 7 to 9 summarize some of the tissue analysis results. Plant tissue analyzed for VOCs and their degradation product TCAA showed that the willows at the 317 FD started in the 1999 growing season to take up and degrade these contaminants, and continued throughout the three growing seasons at rates that were very specific to each single tree analyzed. In general, the levels of contaminants and of their degradation product TCAA were consistently and significantly higher than background (as measured in the control trees) in the trees growing at the French drain location. TCE and PCE (and, though not shown here, carbon tetrachloride and chloroform) were found rarely in the leaf tissue, but consistently in the branch tissue. TCAA in contrast, was found exclusively and consistently in leaf tissue, where it accumulated throughout the summer, typically peaking late in the season, and then reverting to background levels in dead leaves approximately three months from their abscission from the tree (Figures 7 and 8). This data supports the hypothesis that contaminants are transported with the ascending sap to the leaves, where they are degraded to TCAA and subsequently mineralized.

TCE concentrations in branches varied between non-detect and 301 μg/g on a dry weight basis. PCE also varied significantly, between non-detect and 600 μg/g. TCAA was found in the large majority of leaf samples from the contaminated area. For a number of trees, a strong, positive correlation was found between TCAA levels in the leaves and TCE and/or PCE in the corresponding branches at least for subsets of time. Many of these trees were spatially related. A few trees showed relatively elevated levels of TCAA, but quite lower levels of parent compounds, and no correlation between them. This points, among other hypotheses, to the potential presence of other contaminants in the soil that are not currently monitored but that could degrade to TCAA.

The importance of understanding the kinetics of TCE/PCE metabolism and the quantitative correlation between the TCAA and the parent compounds is fundamental to a correct prediction of contaminant uptake and degradation. However, while the data obtained so far clearly confirm plant uptake and at least partial degradation of the contaminants, more work is needed to determine sufficiently accurate removal rates, and the relationship between kinetics of TCAA formation and further degradation and environmental conditions such as radiant energy, ambient temperature, relative humidity, stomatal conditions, sap velocity and general plant metabolic rates. For the time being it is prudent to state that the willows in the FD area are definitely exerting an effect on contaminant removal. This effect is expected to be quantitatively more significant as the amounts of contaminated soil water that is taken up and processed by the plants increases with plant size.

CONCLUSIONS AND RECOMMENDATIONS

The phyto-technologies deployed at the Argonne sites are supplementary to an existing pump-and-treat system. They are intended to enhance the existing environmental protection systems, as well as provide information to assess similar installations. As the trees complete their third growing season in the field, a significant amount of information has been collected to assess their performance at achieving the remedial objectives. From this data, the trees appear to have begun to influence the cleanup area significantly. The deep-planted trees have tapped into the lower contaminated saturated zone and are consuming contaminated water. Degradation of volatile organics is occurring in the plants. Less contamination is reaching the extraction well system than before the plants were installed.

After enduring a transplant shock and below-optimal growth conditions during the first two years in the field, the trees grew at faster rates in 2001. Their increased size is reflected in increased transpiration rates, and presumably larger/longer root systems and enhanced rhizosphere to better influence contaminant reduction and hydraulic control.

Probably the most important remediation mechanism of the planted system is the interception and removal of water from the impacted aquifer. Consequently, the magnitude of transpiration is one of the most critical monitoring parameters: transpiration rates for the trees at the site provide critical information for evaluating current water removal as well as predicting future water usage. Quantified sap flow rates were used to estimate transpiration. Data show that maximum sap flow rates determined during the 2001-growing season are still below the plants' potential, or the estimated hydraulic flux levels. However, the year-to-year increase in rates suggests that across the plantation water use is rapidly closing the gap. These data complement others derived from the recording of groundwater elevation at the site, which show diurnal fluctuations of hydraulic heads in correspondence of elevated daily solar radiation, thus transpiration, during the vegetative season.

Finally, tissue analysis of willows growing at the contaminated source area indicate that TCE and PCE are taken up by the trees in measurable amounts, and that at least a portion of the transported contaminants is degraded in the leaf. The intermediate degradation product appears to be subsequently degraded further in the leaf litter to background levels.

Phyto-technologies are by definition dependant on weather and are equally difficult to predict specifically. The timing of tree growth is as variable as sunshine and cloud patterns, but equally reliable on the average in the long term. For a variety of reasons these planting did not develop as quickly as expected. The question of when trees will be effective is not answered in this demonstration, and that uncertainty must be built into regulatory acceptance and financial considerations of similar applications.

In conclusion, the trees at the Argonne phytoremediation plantation have established themselves for long-term growth, and have begun to positively influence the remediation of the area. Containment is expected for large portions of the plume through hydraulic uptake and contaminant degradation. Modeling based on data collected during the first three years of the project predicts full containment of the 317 plume, and significant containment of the 319 plume.

Table 1. Analyte Levels and c-DCE/TCE Ratio

Well No.	c-DCE (ug/l)	TCE (ug/l)	c-DCE/TCE Ratio
317322	49,000	3,400	14.4
317332	1,400	480	2.9
317342	79	100	0.8

Table 2. Removal of VOCs in 317 Area HC Plantation

	Well 317151			Well 317181		
Analyte	Start (ug/l)	End (ug/l)	Removal (%)	Start (ug/l)	End (ug/l)	Removal (%)
DCA	6,800	4,300	37%	6,100	3,400	44%
TCA	27,000	12,000	56%	6,200	5,500	11%
c-DCE	190	100	47%	71	260	(266%)
TCE	940	1,300	(38%)	230	720	(213%)
Total	34,930	17,700	49%	12,601	9,880	22%

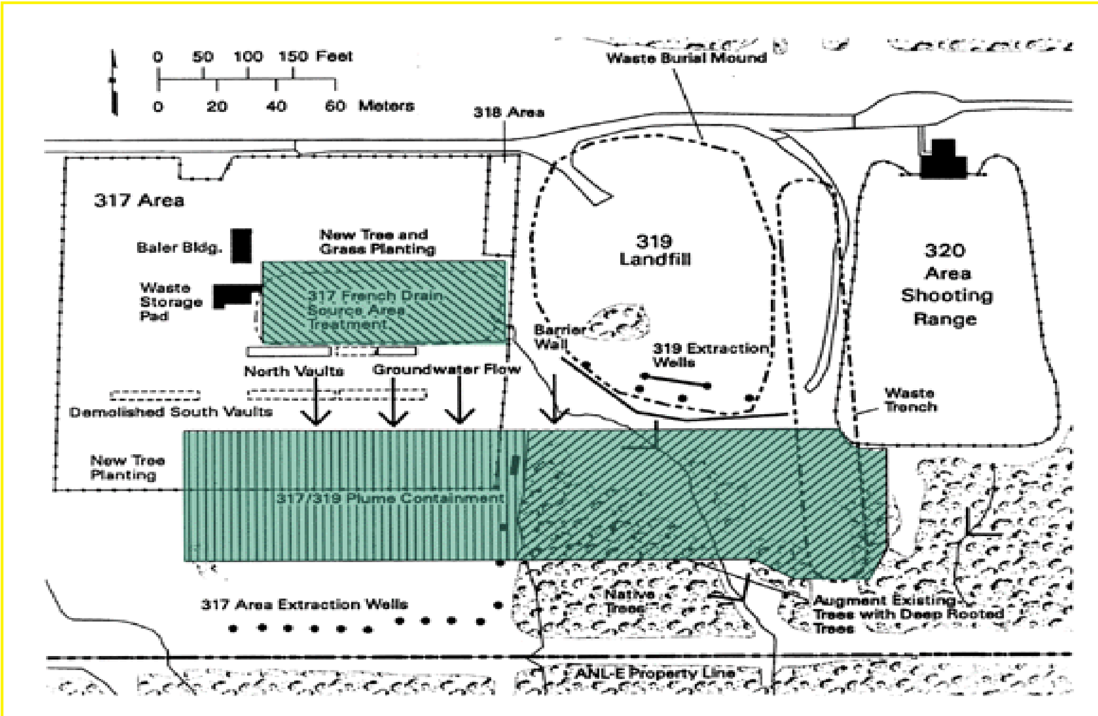

Figure 1. The 317/319 Phytoremediation Area

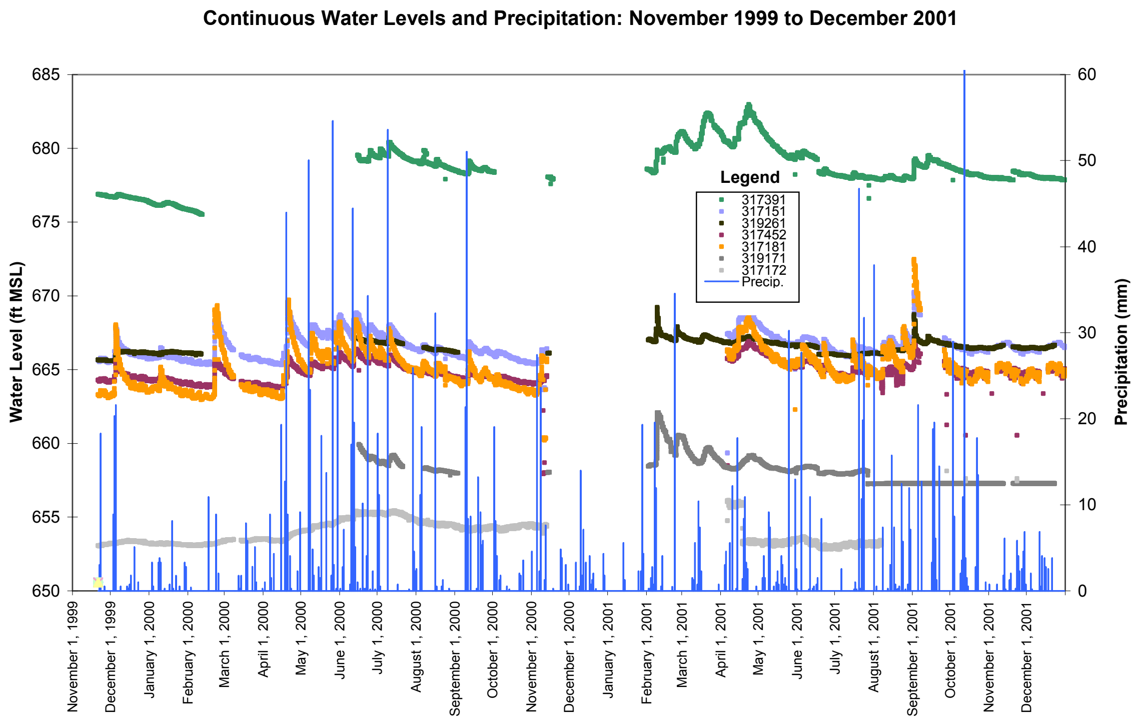

Figure 2. Continuous Water Levels and Precipitation, November 1999 to December 2001

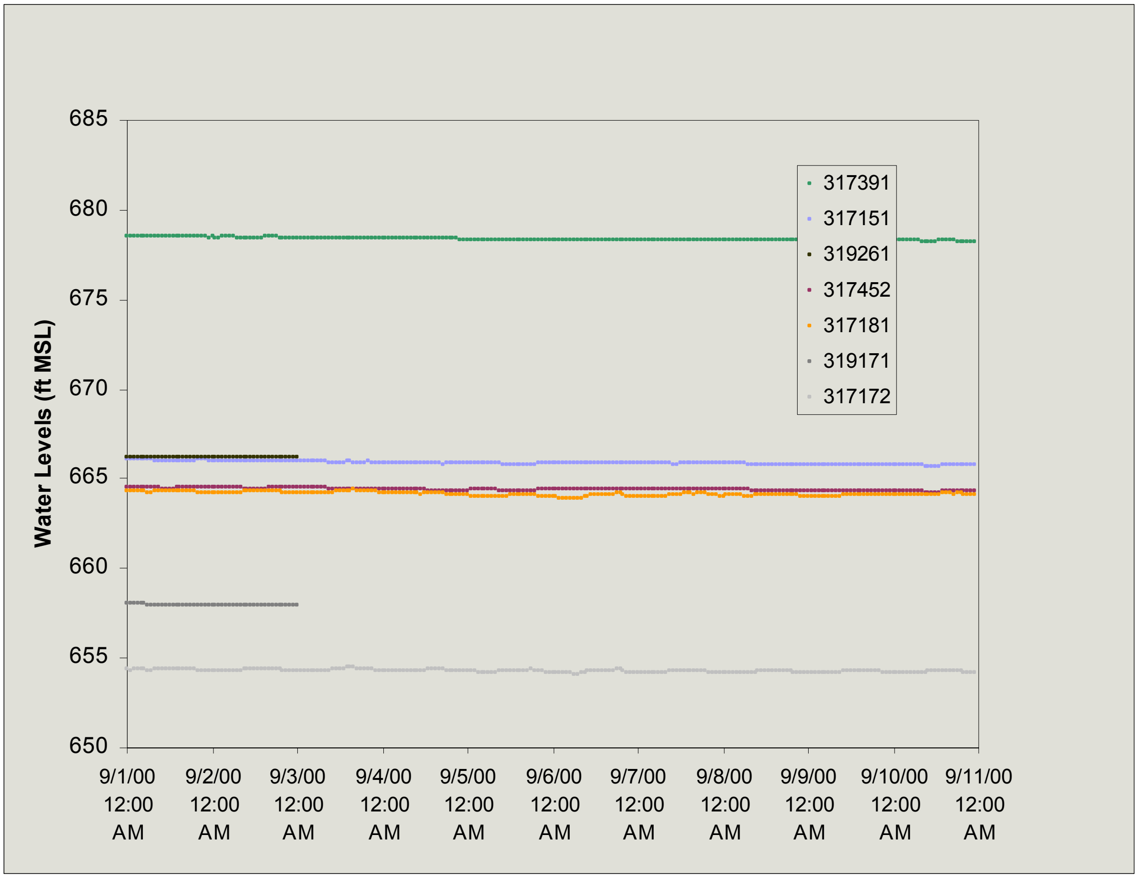

Figure 3. Water Levels, September 1-10, 2000

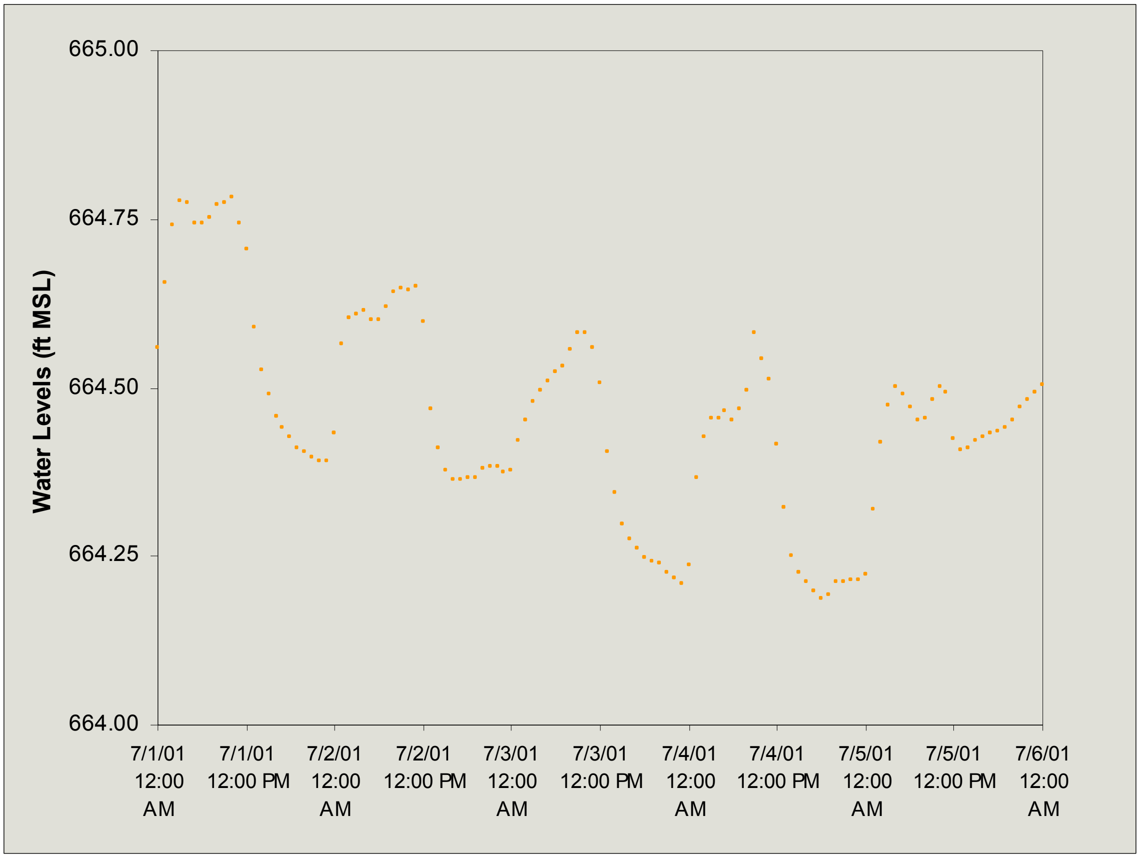

Figure 4. Well 317181 Water Levels, July 1-5, 2001

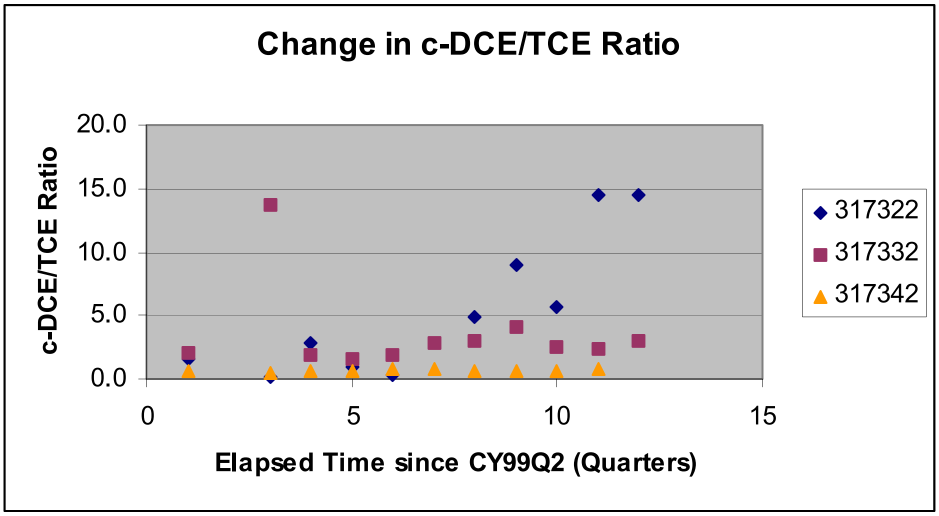

Figure 5. Change in c-DCE/TCE ratio in monitored groundwater wells

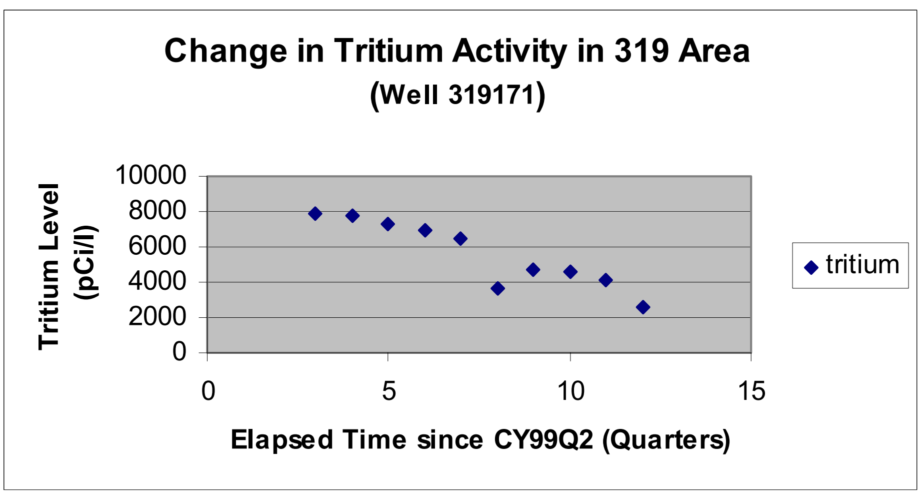

Figure 6. Change in Tritium activity in 319 Area monitored wells

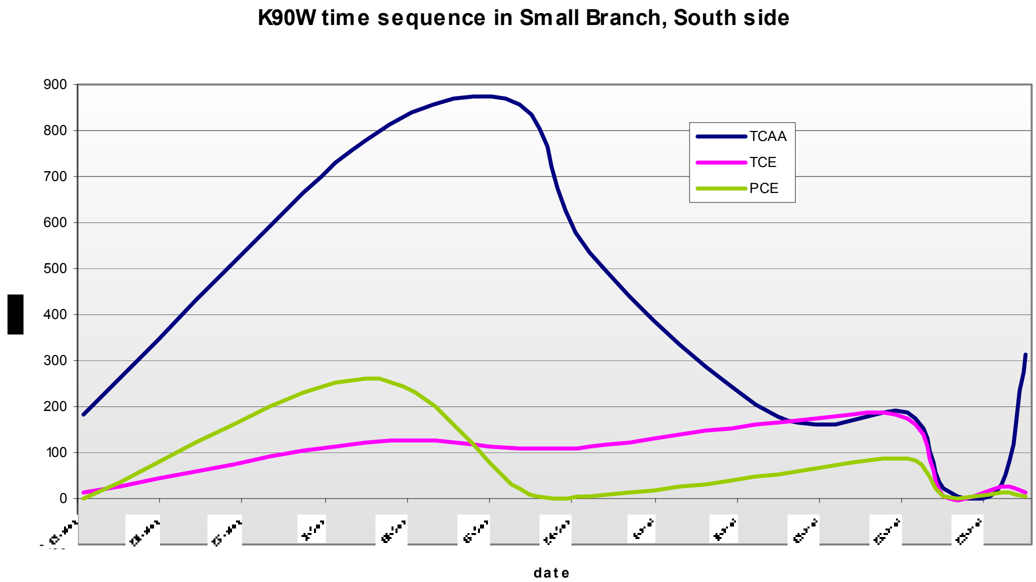

Figure 7. TCE, and PCE in branch, and TCAA in leaf tissue from a willow growing in the FD area

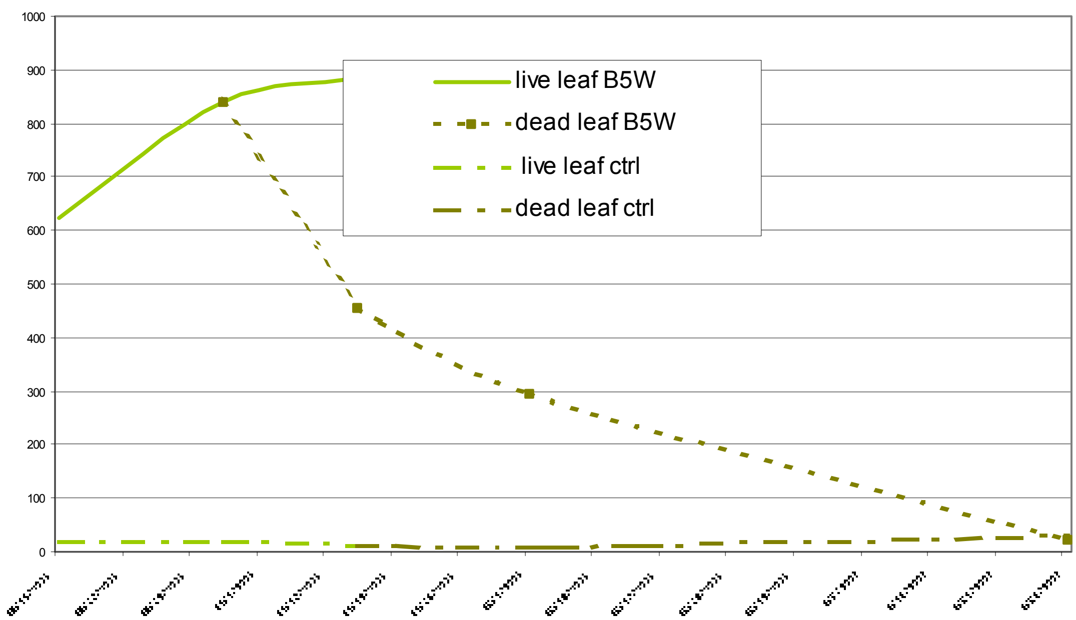

Figure 8. TCAA in live and dead leaves from the FD and control areas

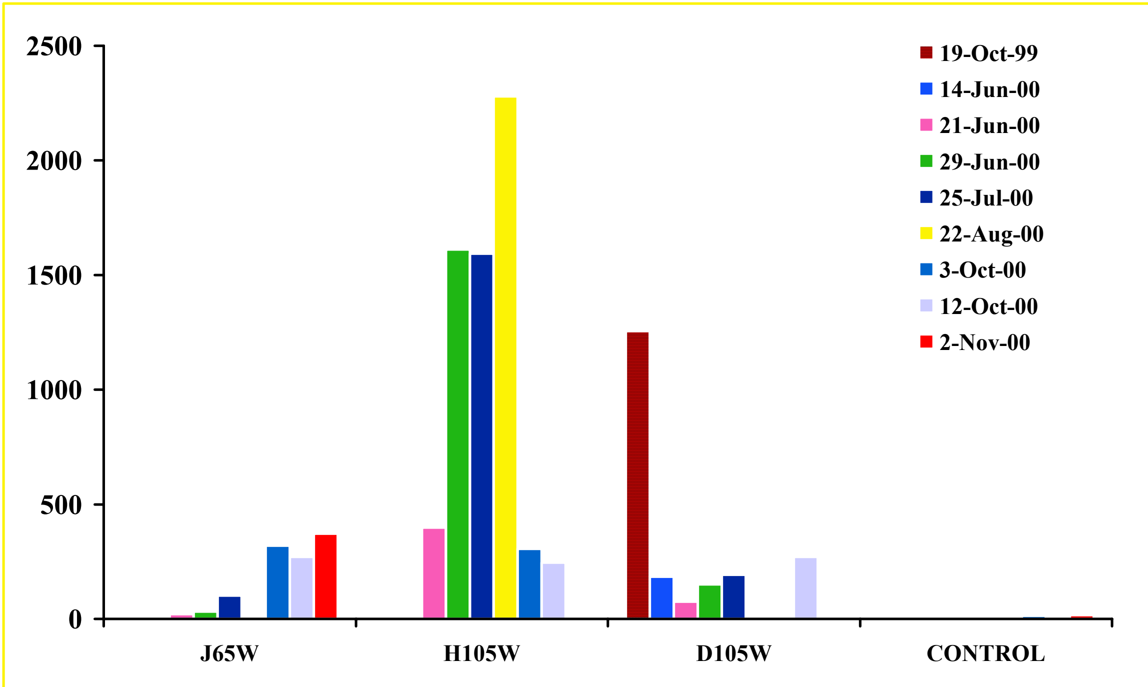

Figure 9. TCAA in leaves of different trees at the FD and HC areas

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